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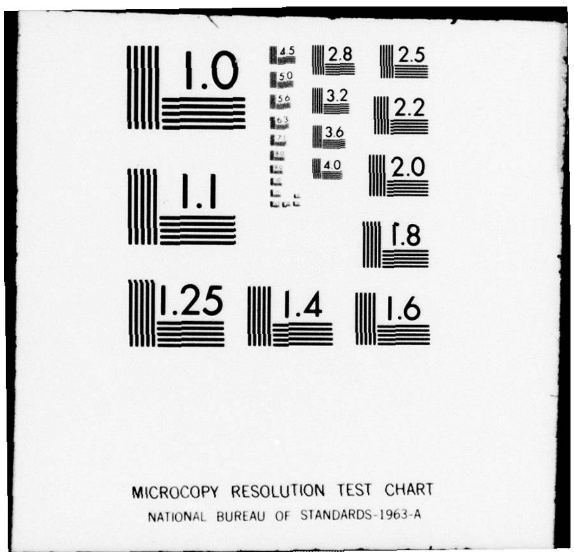
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"REPORT ON ADDITIONAL TESTING AT SALT LAKE
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CONCEPTUAL MODEL,"

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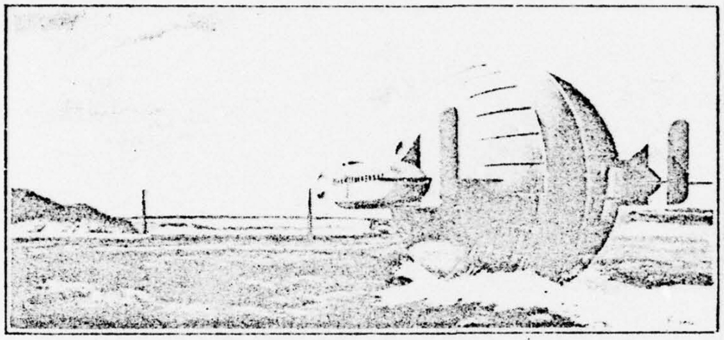

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Prepared for:

Mr. Don Smith, Code 2707/2807
Naval Ship R & D Center
Annapolis Laboratory
Annapolis, MD 21402

(301) 267-2449

Prepared by: New 410 846

Engineering Research and Development Center
College of Engineering
University of Nevada, Reno
Reno, Nevada 89557

(702) 784-6925

(Nevada Univ., Reno.)

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10 Dr. Alex Dandini
Principal Investigator

410 846

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RE: Appendix A
The pages that have the printing cut off are not importmant per Mr. D. Smith, DTNSRDC

I. BACKGROUND INFORMATION

The Hydrosphere is a unique vehicle in that it is both a vehicle and a propulsion system in a single form; that is, the sphere is the vehicle and the rotation of the sphere provides the propulsion. Some years ago, this concept was proved by Dr. Alex Dandini, who is currently with the University of Nevada, Reno. Dr. Dandini designed, fabricated, and successfully operated a ten foot diameter sphere. This sphere had small air propellers on each side for directional control and used a gyroscope for lateral stability. Power for the sphere was provided by a 120 hp Studebaker engine driving six automobile wheels which ran on tracks on the shell's interior. The propelling torque was provided by the weight of the engine being forward of the center of buoyancy. It was noted that under static conditions the depth of submergence was approximately 20% of the sphere's diameter. The exterior was circled by two parallel keel bands, and extending outward from each keel band were 24 propulsion vanes tapering in height from the height of the keel band to about one inch at a distance of three feet outward.

Dr. Dandini operated the Hydrosphere in various sea conditions in and around the San Francisco Bay area. He reported speeds up to 34 mph and observed high propulsion efficiency (low slip), amphibious operation, and excellent stability. The Hydrosphere was destroyed in a fire before more advanced development could be undertaken. Many years then elapsed before the U.S. Navy became interested in unique concepts for rollercraft and propulsors which operate through air-water interfaces. A meeting was held at the Naval Ship Research and Development Center, Annapolis (NSRDC/A), March, 1973, wherein various new concepts

were discussed. Among these was the Hydrosphere as presented by Mr. D.F. Smith (NSRDC/A). It was decided that basic experiments should be conducted with the Hydrosphere concept to determine such factors as:

- size and scaling effects in order to justify extrapolation of model results to full size systems
- vane spacing and confirguration in order to optimize system performance
- characterize the Hydrosphere using the concept of "propulsion efficiency"

A study was conducted at the Desert Research Institute (DRI), University of Nevada System, during the period of July 1, 1973 to June 30, 1974. The study involved the design, fabrication, and testing of a three foot diameter Hydrosphere model. Various tests were conducted by the DRI to determine the effects of various vane spacings and configurations, the amount of slip, and qualitative information concerning power, stability, and smoothness of performance. Some useful data resulted from these previous studies, namely, proof of concept, slip data as a function of sphere diameter, vane design information, and qualitative data in the form of movie film. It was concluded that a larger diameter sphere should be designed, fabricated, and tested to determine scaling effects as a function of diameter. A seven foot diameter sphere was chosen, primarily due to the availability of a mold for fabrication of the sphere using fiberglass.

Scientific Engineering Systems, Inc. of Reno, Nevada was awarded a subcontract by the University of Nevada, Reno to provide engineering services for the management, design, fabrication, and testing phases of

the seven foot Hydrosphere program. The actual cost of materials, sphere fabrication, machine shop work, and instrumentation was subcontracted on a direct cost basis. The University of Nevada provided special facilities, instrumentation, and limited support whenever possible.

The seven foot Hydrosphere was successfully designed, fabricated, and subjected to initial testing. There have been several reports prepared and submitted to NSRDC/Annapolis during these past few years, namely:

Interim Report I - This report provided background information, theoretical discussions, preliminary design information including structural, power plant considerations, control systems, weight estimates, and experimental procedures.

Interim Report II - This report provided a detailed summary of the various design options considered, the selection of a design method, a design report including structural, control systems, propulsion vane design, engine components, and proposed data acquisition methods.

Interim Report III - This report provided a submission summarizing fabrication procedures, problems encountered, and techniques employed leading to the final assembly of the seven foot Hydrosphere.

Final Report - Part I, August 14, 1975 - This report included a brief outline of each of the above noted Interim Reports, as well as detailed discussions covering the periods of testing. The initial data gathered was presented along with preliminary conclusions and recommendations.

Final Report - Part II, October 20, 1975 - This report included a discussion about throttle control system changes that provided improved

steady state performance. Additional testing was accomplished and the results presented in this report. A more detailed discussion of the theoretical aspects of dynamic similarity was presented with specific applications being made to the Hydrosphere concept. A review of 3 ft data was made and the results were also summarized in this report. Conclusions and recommendations for future work were included.

The Hydrosphere model was operated satisfactorily and, in the opinion of an outside consultant, Dr. Allen Acosta, "...the data obtained are meaningful and represent real physical events for the operation of the Hydrosphere." The basic problem was that there was not sufficient funding available to gather the extensive data required to provide a technical base for the evaluation of the Hydrosphere propulsion concept.

There was, therefore, a major justification for additional testing centered around the fact that the University of Nevada had developed an operating model of the Hydrosphere and the performance data taken on this model indicated significant potential for some naval applications. The data were not, however, sufficient to provide an explanation for a significant scattering of data points. An additional contract was let to the Engineering Research and Development Center (ERDC), University of Nevada, to develop and conduct a test program, utilizing the seven foot model for the purpose of generating supplemental data necessary to resolve this apparent disparity and to establish the feasibility of this concept for a variety of potential Navy operational applications.

A subcontract was let to Scientific Engineering Systems to aid the ERDC in developing, conducting, and reporting on this additional test program. A suitable test plan was prepared and submitted to the Navy for approval. The results of these additional field tests were described in

the report, "Performance Tests and Analysis on a 7 Ft Hydrosphere Model," January 14, 1977.

A number of test runs were made at two fresh water lakes near Reno, Nevada, i.e., Boca Reservoir and Lake Tahoe. The data course was set up in each case parallel to the shoreline. The length of the course for the additional testing program was 150 feet. A 16 mm camera was used to record the test runs and a stop watch used to provide run times. A summary of the raw and processed data gathered was included in this report. The Hydrosphere model was operated in several modes, namely, self propelled (free running), self propelled (towed), locked sphere (towed), free rolling (towed), and reverse free rolling (towed).

A special underwater camera was fabricated in order to accomplish under water filming in the clear waters of Lake Tahoe. Excellent films were obtained that proved useful for studying the sphere-water interface under dynamic conditions. A computer program was developed in order to help speed up the task of data processing. This report resulted in the following general conclusions and recommendations:

The Hydrosphere concept has been evaluated in detail and attempts made to quantify performance parameters. Extensive experimental data have been gathered and analyzed in an effort to describe and predict Hydrosphere performance characteristics. This new propulsion concept exhibits very complex flow characteristics, especially when compared to the more conventional watercraft. The work accomplished to date does, however, allow several conclusions to be reached.

(a) The Hydrosphere concept produces a stable operating system.

(b) Excellent lift-drag ratios can be obtained even at significant slip; however, when speed is of concern additional consideration must be given to the slip parameter.

(c) The Hydrosphere exhibits definite "multi-mode" characteristics. This means that the craft can be operated in a low slip and correspondingly higher velocity mode, that is quite different from that of a conventional planing watercraft.

(d) The Hydrosphere can be operated over a wide range of velocity and drag-lift ratios. The concept provides a number of interesting alternatives for proposing new types of multi terrain vehicles.

(e) It is not understood at this time what operating parameters are the most critical to operating the Hydrosphere in the highly efficient low slip mode.

(f) The rolling sphere was less susceptible to wind loading than was the "locked" sphere. Also, the rolling sphere developed less total drag than the locked sphere.

(g) The Hydrosphere is basically a boundary control type watercraft. It has been shown that there are definite modes wherein highly efficient low slip operation can be achieved. The effects of towing were not very great in that little was gained by applying significant towing power to the sphere. It is felt that this is because of the experimental difficulty in towing the Hydrosphere with the proper degree of forward slip, which may be necessary to achieve the low drag mode.

(h) The 7' Hydrosphere "optimum" mode occurred in all cases when the angular velocity, ω, was between $.32 \leq \omega \leq .39$.

(i) The Hydrosphere operates in an amphibious mode.

There are still several important questions to be answered before one can understand and characterize the Hydrosphere concept. One basic question is how to model and scale Hydrospheres, since it is still not clear what methods or parameters can be used for scaling performance to larger spheres. The general wave generating characteristics appear to be similar when one observes the wave generating performance of the 3', 7', and 10' Hydrospheres; however, the effect of loading had not been determined.

It was decided that the next step in the Hydrosphere program should be a special set of tests designed to evaluate Hydrosphere performance under a different loading condition. This was not possible to accomplish within the present experimental project because the 7 ft Hydrosphere model was already operating at a 17% submergence level and it was not possible to lighten the model. It was felt that it should be possible, however, to operate and gather performance data on a body of water having a greater density. This would have somewhat the same effect as lessening the load. For example, it was felt that performance runs on the Great Salt Lake in Utah might provide a suitable set of data to evaluate Hydrosphere performance under a controlled loading condition. Such a set of data could also provide a basis for determining whether or not loading is a significant factor to having the Hydrosphere operate in its higher velocity-lower slip mode.

It is the results of this set of experiments, conducted at Salt Lake in Utah, that is the central theme of this report. Also included, however, are conclusions and recommendations for future work on this most unique and interesting amphibious watercraft concept.

II. EXPERIMENTAL PROCEDURES

The original test plan called for the experiments to be conducted at the South shore of the Great Salt Lake. There is a marina for sailboats not far from downtown Salt Lake City, Figure (1). The first attempt to launch the Hydrosphere on the morning of January 4th was cancelled because the marina was covered by heavy fog. It was then decided to move the experiments North to an area just West of Ogden, Utah. This site required obtaining permission from the Great Salt Lake Mineral and Mining Company to cross their land and reach the Lake. This site turned out to be ideal for the experiments. The water was protected from the wind, and was deep enough (in excess of 15 feet) to easily conduct the experiments. Also of interest is the fact that the density of the water in the Northern area is much more dense than that in the South due to construction some years ago of a railroad causeway across the Lake. The specific gravity in the area where the tests were finally conducted was found to be 1.22. This data was provided by Walt Katzenberger who is in charge of the Utah Geological Survey. Mr. Katzenberger gathers such density data routinely over the entire Great Salt Lake area.

The tests were finally conducted in the area shown marked in Figure (2). The course was set up parallel to the shoreline. The length of the course was 150 feet which was marked off by two buoys. A 16 mm camera was used to record the test runs and a stopwatch used to measure run times. A summary of the data gathered is shown in Appendix "A." A record of the films taken is shown in Appendix "B." It should be noted that previous data have been listed as runs 1 through 205 and have been documented in the report entitled, "Performance Tests and Analysis on a 7 Foot Hydrosphere Model," January 14, 1977. These were all fresh water

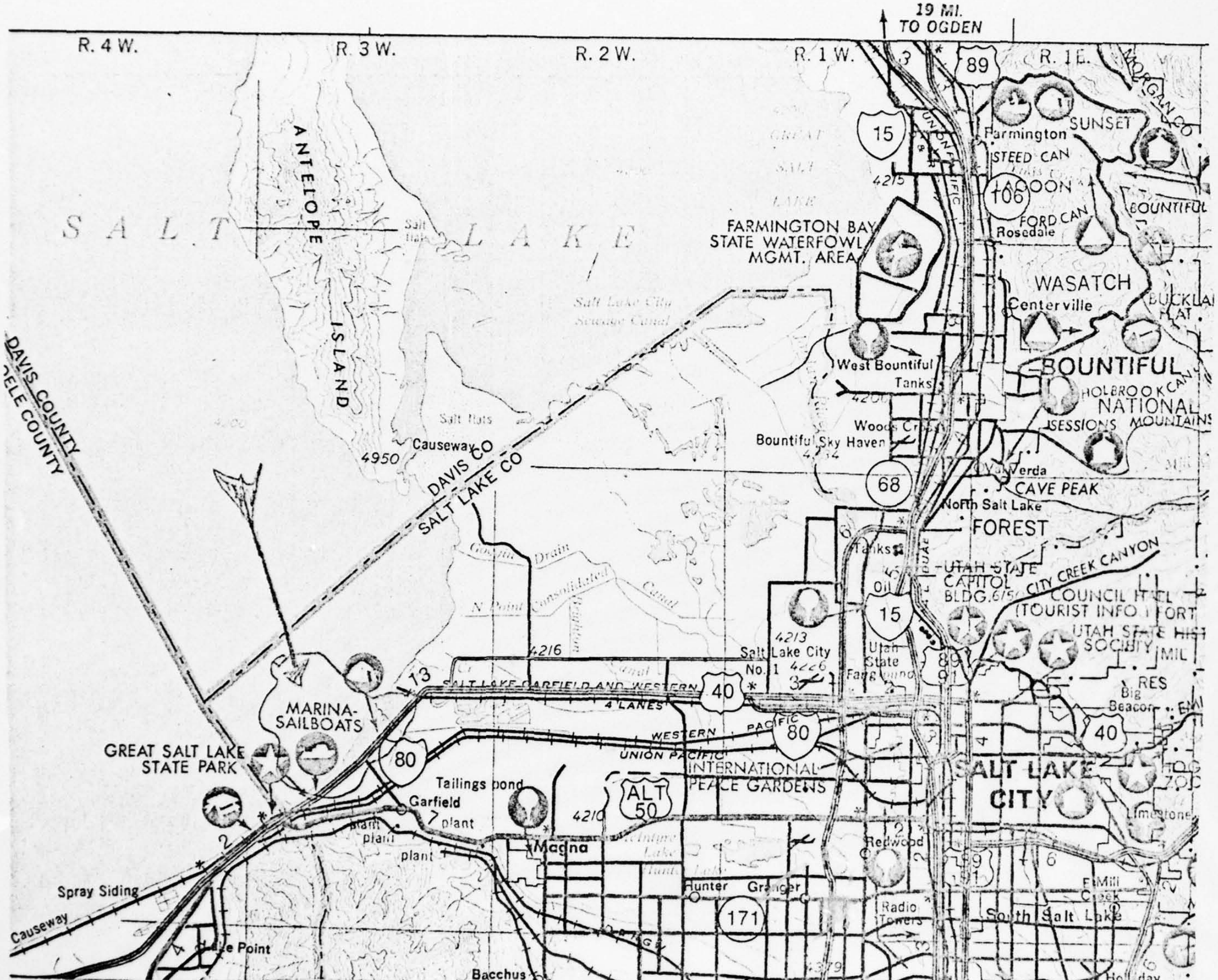


Figure (1). Map showing area of South shore where tests were originally planned.

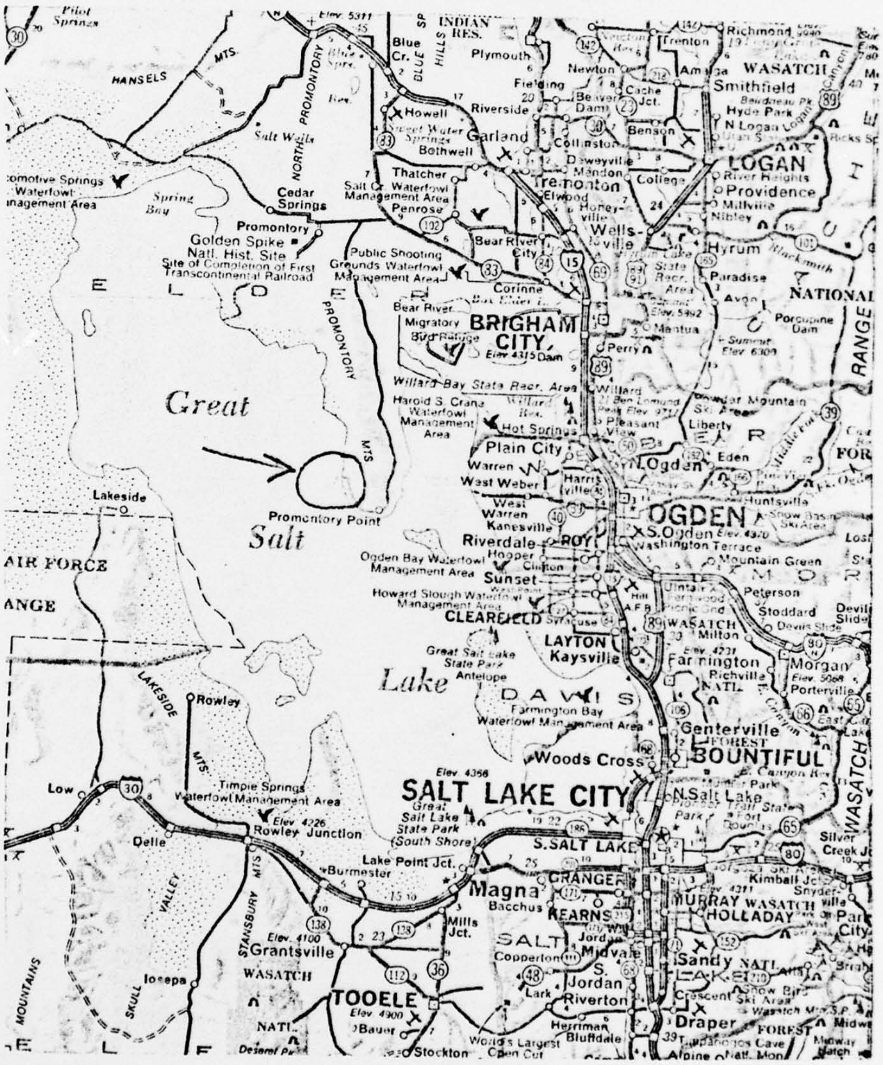


Figure (2). Area West of Ogden, Utah where experiments were conducted January 4-7, 1978 on the Great Salt Lake.

runs. It was decided that these runs in salt water be listed using consecutive numbers starting with 206. The following description briefly explains the type of experiments conducted during each set of runs.

1. Runs 206-229 (inclusive). These data were taken while operating the Hydrosphere in a self-propelled mode over the 150' measured course.
2. Runs 230-235 (inclusive). These data were taken while the Hydrosphere was operating in a self-propelled mode; however, the Hydrosphere shell had 48 extra vanes attached to the outer surface. A detail of a typical vane is shown in Figure (3).
3. Runs 236-241 (inclusive). These data were gathered while towing the Hydrosphere in a "locked" condition, that is, the sphere was pulled through the water without rotation. This was accomplished <u>without</u> the addition of the extra aluminum vanes.

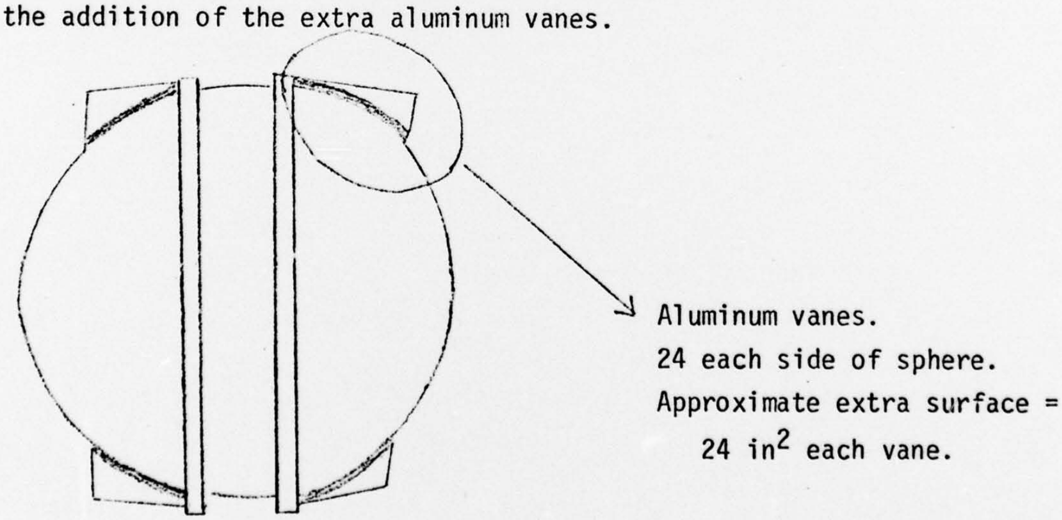


Figure (3). Sketch showing position and size of the extra aluminum vanes added for additional testing.

III. MATHEMATICAL DISCUSSIONS

There are a number of useful relationships that can be derived for the Hydrosphere. Reference is made to Figure (4).

a. Submerged projected cross sectional area, A_s

$$A_s \approx 0.8\, D^2\, F^{3/2}\, \left[(1-F)^{1/2} + 0.67\right]$$

where

D = the diameter of the sphere

F = fractional part of diameter submerged

b. Submergence volume, V_s

$$V_s = \pi h^2\, (R - h/3)$$

where

h = submergence depth

R = radius of sphere

c. Wetted surface area, A_W

$$A_W = \pi F D^2$$

where

F, D are defined above

d. Drag coefficient, C_D

$$C_D \triangleq \frac{2gP\ (550)}{\rho A_s V^3} = \frac{1100\ Pg}{\rho A_s V^3}$$

where

A_s = submerged projected cross section (ft^2)

P = power (hp)

g = gravitational constant (32.2)

ρ = density of the fluid (lbs/ft^3)

V = velocity of the center line of the sphere (ft/sec)

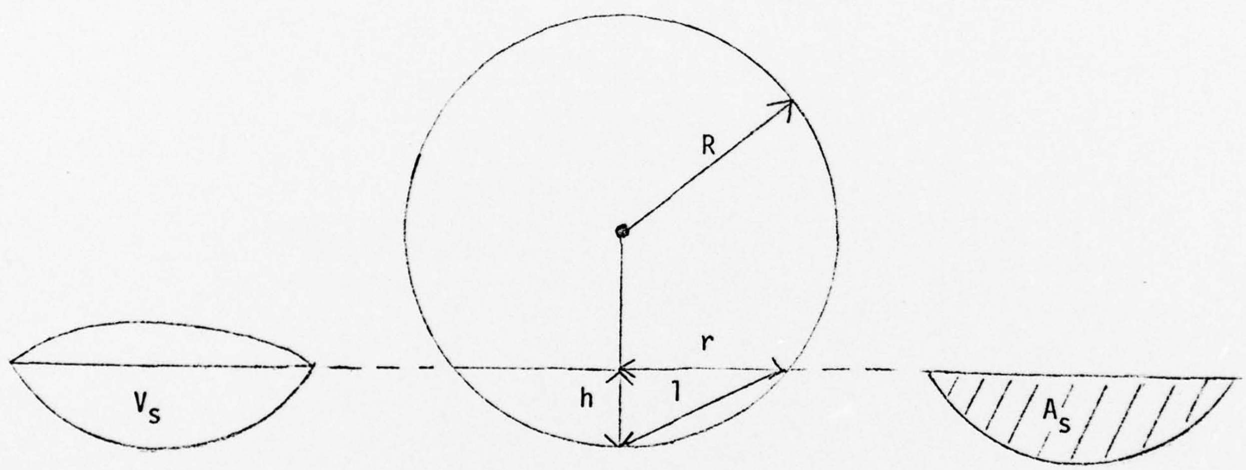


Figure (4). Geometry for a partially submerged sphere.

d. Froude Number, F_r

$$F_r = \frac{V}{(gD)^{\frac{1}{2}}}$$

where

V = velocity of center line over water (ft/sec)

D = diameter of sphere

g = gravitational constant (32.2)

It should be noted that for the fresh water runs the characteristic parameter in the Froude number above was selected to be the characteristic dimension. Since the latest tests were conducted in a more dense fluid, thus creating less submergence it was felt that the actual water line length would be a better parameter to use. The water line length for the fresh water tests can be computed using

$$C = 2\pi\ (2Rh - h^2)^{\frac{1}{2}}$$

where

h = submergence depth

R = radius of the sphere

For fresh water

$$h = .178\ (7) = 1.246 \text{ ft}$$

and for salt water

$$h = .160\ (7) = 1.12 \text{ ft}$$

$$C_1 = 2\pi\ (2(3.5)\ (1.246) - (1.246)^2)^{\frac{1}{2}}$$

$$= 16.82 \text{ ft}$$

$$C_2 = 2\pi\ (2(3.5)\ (1.12) - (1.12)^2)^{\frac{1}{2}}$$

$$= 16.12$$

Since there is only a 4% difference in the scale parameter and since the Froude number is a weak function of the scale parameter a correction factor was not felt to be necessary and therefore the diameter of the sphere D = 7 ft was used for all fresh and salt water comparisons using F_r.

e. Effective lift drag ratio, η_t

$$\eta_t = \frac{P}{WV}$$

where

W = total weight of the craft (940 lbs)

V = forward velocity of center line (ft/sec)

P = power applied (ft-lb/sec)

III. GRAPHICAL PRESENTATION OF THE DATA

A plot was made, Figure (5), of the "effective" drag coefficient C_D as a function of Froude number F_r for the Hydrosphere under "locked" sphere conditions. These points are represented as runs 236 - 241 (inclusive) and are shown compared to the fresh water data runs 163 - 174 (inclusive) also under "locked" sphere conditions. The following expressions were used.

The Froude number has been defined as follows:

$$F_r = \frac{V}{(gD)^{\frac{1}{2}}}$$

where

V = velocity of center line over water (ft/sec)

D = diameter of sphere (ft)

g = gravitational constant (32.2)

The factor C_D is given by

$$C_D = \frac{1100Pg}{\rho A_s V^3}$$

Where for the salt water tests

$$e = 1.22 * 62.4 = 76.13$$

and

$$A_s = 0.8D^2 F^{3/2} \left[(1-F)^2 + 0.67\right]$$

$$D = 7 \text{ ft}$$

$$F = .16$$

$$= 3.98 \text{ ft}^2$$

then

$$C_D = \frac{(1100)(32.2) P}{(76.13)(3.98)V^3} = 116.7\frac{P}{V^3}$$

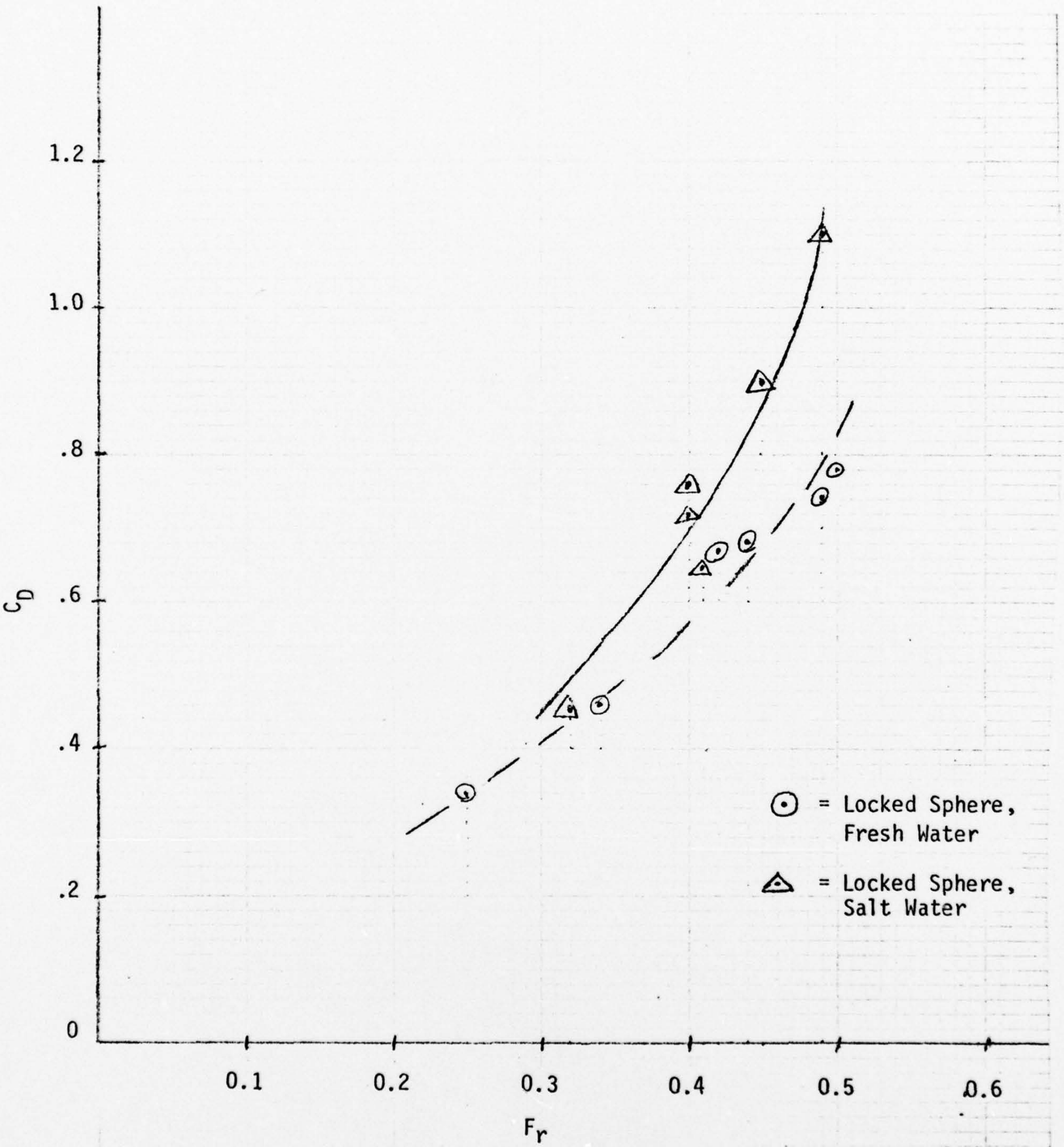


Figure (5). A plot of C_D vs F_r for fresh and salt water "locked" sphere data.

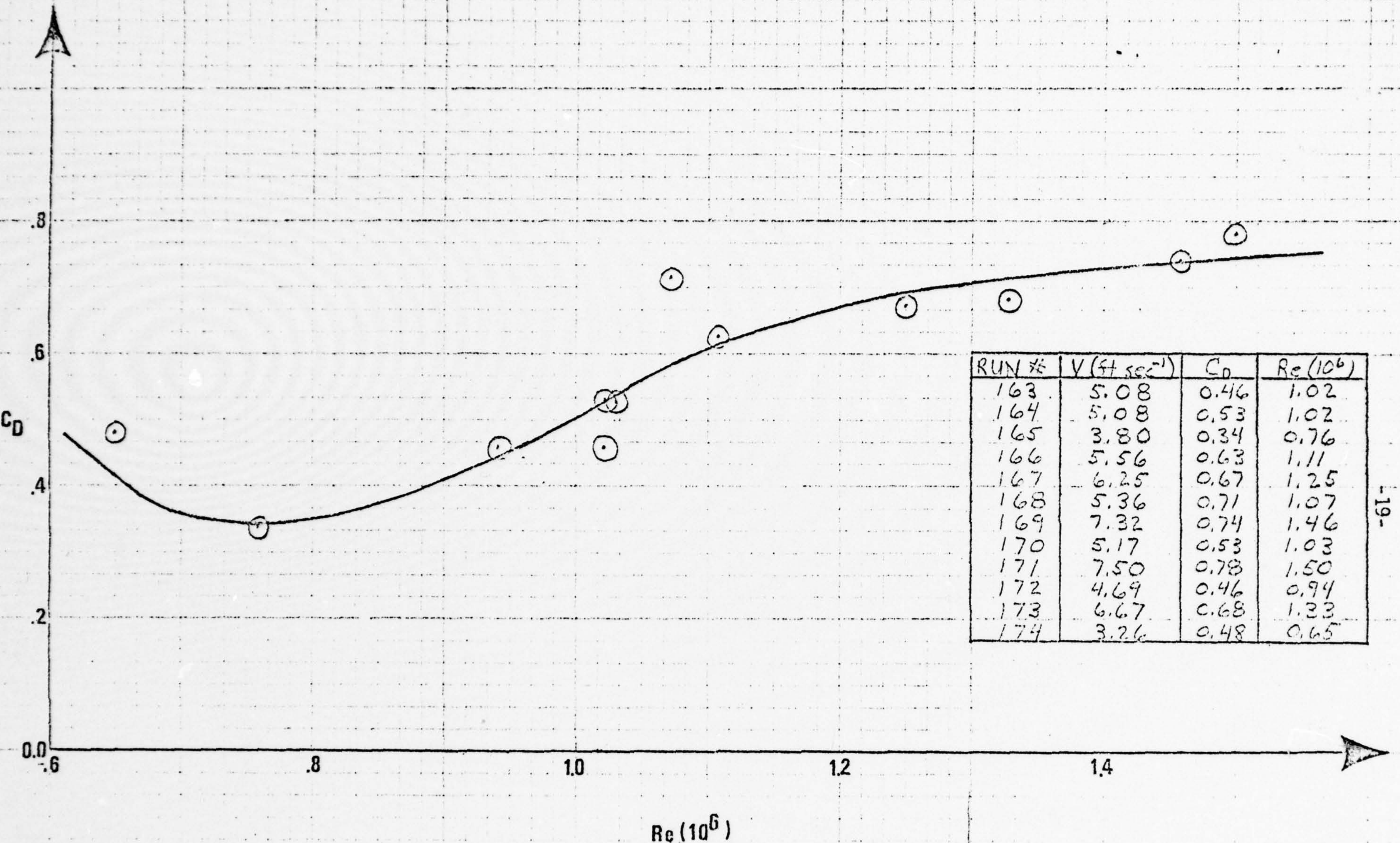
It appears from the data that for Froude numbers $F_r > 0.3$ the measured drag coefficient C_D is larger for salt water than for fresh water. This is true even though the sphere sits "higher" in the salt water than it does for the fresh water. Note also that the total "wetted" area for the salt water case, A_{ws} was approximately 10% less than for the fresh water case, A_{wf}. This follows from:

$$A_{ws} = \pi F_s D^2 = \pi(.16)\ (7)^2 = 24.6\ ft^2$$

$$A_{wf} = \pi F_f D^2 = \pi(.178)\ (7)^2 = 27.4\ ft^2$$

The flow pattern in the wake of the Hydrosphere depends on the Reynolds Number of the flow. It is useful, therefore, to consider a plot of Reynolds Number versus the effective drag for the Hydrosphere. It is well documented in the literature that the drag coefficient for a completely submerged sphere exhibits reduced drag when the boundary layer becomes turbulent. This reduction is somewhat more gradual for a sphere than that for a streamlined body because of the smaller contribution made by the pressure drag to the total drag of the streamlined body. A plot of the Reynolds Number, R_e versus the effective drag coefficient, C_D is shown in Figure 6. This data is for the locked sphere and towing mode (runs 163-174). The data indicates that a critical Reynolds Number of approximately 0.8×10^6 exists where the boundary layer becomes turbulent. There does not appear to be a region where C_D becomes independent of R_e at least over the limited ranges of R_e that were measured.

Some interesting comparisons can also be made between the data gathered in fresh water, salt water, and in salt water with the additional vanes attached. Table I shows a set of data for each of these cases grouped according to average values selected over a narrow range of ω.



RUN #	V (ft sec^{-1})	C_D	Re (10^6)
163	5.08	0.46	1.02
164	5.08	0.53	1.02
165	3.80	0.34	0.76
166	5.56	0.63	1.11
167	6.25	0.67	1.25
168	5.36	0.71	1.07
169	7.32	0.74	1.46
170	5.17	0.53	1.03
171	7.50	0.78	1.50
172	4.69	0.46	0.94
173	6.67	0.68	1.33
174	3.26	0.48	0.65

Figure (6) - Plot of C_D vs Reynolds number for locked rotor

	Case	ω R/sec	Slip %	Vel ft/sec	Power hp	F_r	C_D	η_t	V_{CL}/ω
$0.75 \le \omega \le 0.77$									
32,37	I	.77	60.7	6.67	3.42	.44	1.38	.30	8.6
208,213	II	.76	64.1	5.96	4.15	.40	2.29	.41	7.8
None	III	-	-	-	-	-	-	-	-
$0.62 \le \omega \le 0.63$									
75,85,88,89,150,155,157	I	.63	56.9	5.94	1.64	.39	0.94	.16	9.4
228,229	II	.63	56.3	6.07	2.08	.40	1.08	.20	9.6
None	III	-	-	-	-	-	-	-	-
$0.56 \le \omega \le 0.61$									
133,134,136,142,143,152, 159	I	.59	58.3	5.44	1.58	.36	1.21	.17	9.2
212,225,226	II	.59	54.9	5.88	1.78	.39	1.03	.18	9.97
230,231,232,235	III	.59	49.6	6.67	2.51	.45	.98	.22	11.3
$0.52 \le \omega \le 0.55$									
34,65,66,72,131,132 135,137,141,162	I	.53	49.4	5.92	1.15	.39	.70	.11	11.2
206,210,219,220, 221,224,227	II	.54	53.6	5.74	1.28	.38	.80	.13	10.6
None	III	-	-	-	-	-	-	-	-
$0.48 \le \omega \le 0.51$									
82,83,129,153	I	.49	51.0	5.28	.64	.35	.52	.07	10.7
207,209,214	II	.50	51.8	5.34	1.00	.36	.77	.11	10.7
234	III	.49	45.4	5.92	1.4	.39	.79	.14	12.1
$0.42 \le \omega \le 0.47$									
73,80,81,84,128,129 140,145,149,161	I	.45	48.6	5.07	.82	.34	.80	.10	11.3
216,218,222	II	.46	51.2	4.95	.71	.33	.45	.07	10.8
233	III	.42	41.9	5.41	.73	.36	.54	.08	12.8
$\omega = 0.31$									
123,125,127	I	.32	40.0	4.21	.03	.28	.06	.005	13.2
211	II	.31	38.0	4.25	.66	.28	1.0	.091	13.7
None	III	-	-	-	-	-	-	-	-

Table I - Data separated into ranges of ω.
Average values for runs shown.

Case I - This is data in fresh water (no extra vanes)

Case II - This is data in salt water (no extra vanes)

Case III - This is data in salt water with all 48 extra vanes added.

A plot was then made of the ratio of forward velocity divided by ω for the various values of ω considered. This plot is shown in Figure (7). It is noted that the data for Cases I and II fall on a straight line indicating that this parameter is independent of the density of the fluid. Also of interest is the fact that when the additional vanes were added a significant improvement resulted in the ratio of V_{CL}/ω or for a given ω an improvement in the forward velocity, V_{CL}.

It appears, therefore, that the parameter ratio of V_{CL}/ω may be a useful one for the design of a Hydrosphere.

The experiments with the extra vanes led to some other interesting results. There was, as expected, a reduction in slip as well as a corresponding increase in forward velocity. It was desired to determine what cost in power resulted from the increased forward velocity. All of the runs for Case II and III were averaged resulting in the following values.

Case II (salt water, no vanes)

$\hat{\text{Slip}}$ = 53.3%

$\hat{V}_{CL}/\omega$ = 10.4

$\hat{\text{Power}}$ = 1.6 hp

Case III (salt water with vanes)

$\hat{\text{Slip}}$ = 47.6%

$\hat{V}_{CL}/\omega$ = 11.8

$\hat{\text{Power}}$ = 2.03 hp

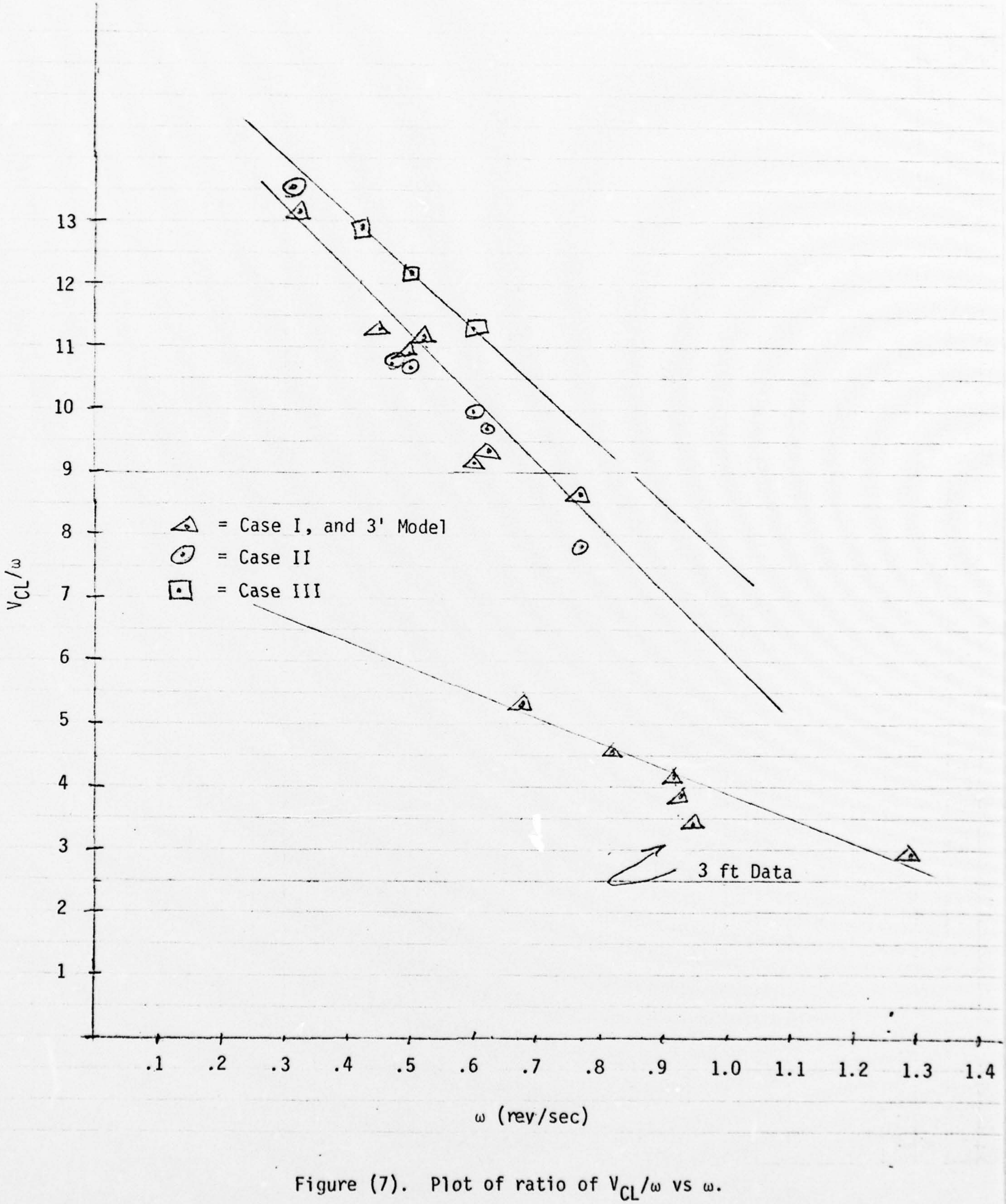


Figure (7). Plot of ratio of V_{CL}/ω vs ω.

The ratio of velocity improvement is then calculated to be

$$\frac{V_{CLII}}{V_{CLI}} = \frac{11.8}{10.4} = 1.13$$

The corresponding power penalty can be computed from the ratio

$$\frac{P_{II}}{P_{I}} = \frac{2.03}{1.6} = 1.27$$

This calculation indicates that the improvement in velocity was achieved at a power "cost" of approximately the velocity squared, i.e.,

$$(1.13)^2 = 1.27$$

This is an interesting result indicating that the extra vanes were quite power efficient in improving the forward velocity of the Hydrosphere. This supports the concept that the vanes assisted in the detachment of flow from the sphere, thus reducing the total drag.

It is instructive to consider the non-rotating sphere tests that were conducted in both fresh and salt water. Towing "locked sphere" tests were conducted in fresh water using both a 3' and a 7' sphere. It was observed that the 3' sphere experienced a significant "negative lift." In fact in some cases, as the 3' sphere was towed through the water at the higher velocities the negative lift forces "pushed" the sphere down into the water. At times this was to a level of over 60% of the diameter submerged. An explanation for this is in the balance of forces that must exist between buoyancy and Bernoulli type forces, the latter being present due to the increased velocity of flow under and around the sphere resulting in a corresponding decrease in pressure.

The 7' sphere, however, did not experience such a severe case of "negative lift." The explanation for this can be found when one considers

the ratio between the wetted surface areas, A_w, the displaced volume, V_s, and the diameter, D. Consider the following relationships:

$$A_w = \pi F D^2$$

and

$$V_s = \pi h^2 (R - h/3)$$

where these terms are defined earlier in Section III.

Assume that the sphere is submerged to 20% of the diameter, i.e.,

$$F = .2, \quad h = FD = .2D$$

Then

$$A_w = \pi(.2)\,(2R)^2 = 0.8\pi R^2$$

and

$$V_s = \pi(.4R)^2 \left(R - \frac{.4R}{3}\right) = \pi(.16)R^2\,(.867R)$$

and the ratio A_w/V_s is given by

$$\frac{A_w}{V_s} = \frac{0.8\pi R^2}{\pi(.16)R^2(.867R)} = \frac{1}{.1734R}$$

In terms of the diameter then this becomes

$$\frac{A_w}{V_s} = \frac{1}{0.0867D}$$

This ratio indicates the sensitivity of the Bernoulli forces (proportional to wetted surface area, A_w) to the buoyancy forces (proportional to the displaced volume, V_s). A plot of this ratio vs diameter, D is shown in Figure (8).

The significance of this can be understood by considering the vertical components of forces acting upon the moving sphere. Thus, at constant speed, the vertical forces must sum to zero for the sphere to maintain a constant submergence. Two types of forces may be considered: the buoyancy pressure forces due to the ρgZ pressure gradient in the fluid at rest, and the pressure forces due to the induced flow around the sphere.

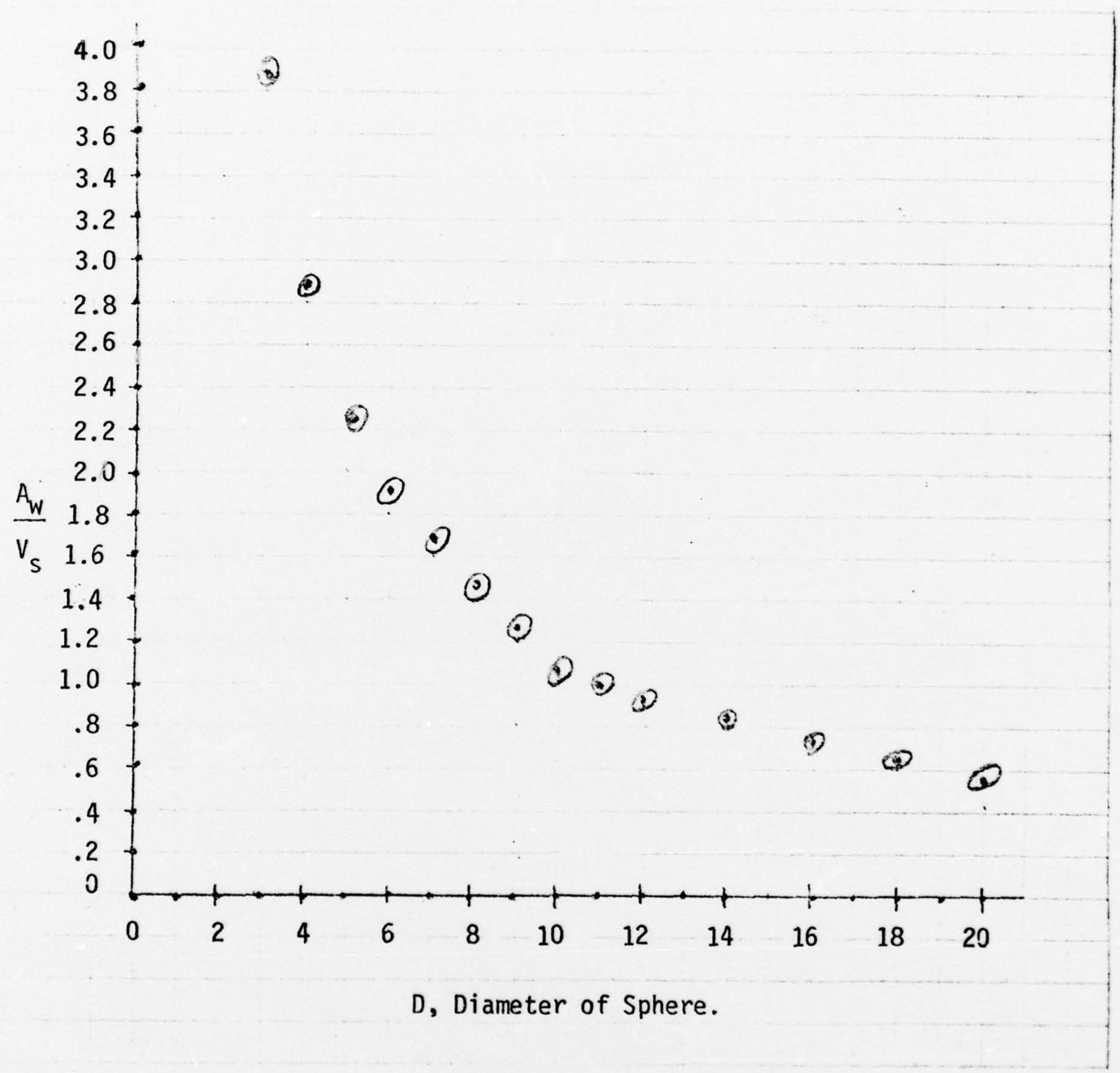


Figure (8). Plot of ratio A_W/V_S vs D showing sensitivity.

The flow dependent pressure forces can be zero, greater than zero, or less than zero, and must be integrated over the entire submerged surface to determine their effects. It is, however, apparent from the sinking action of the moving sphere that the sum of the flow induced forces is less than zero. The fact that the buoyancy (static) pressure forces increase linearly with diameter is the reason that a larger sphere sinks a smaller fraction of diameter than a small sphere at the same speed. That is, the average pressure of the fluid on the sphere (at rest) is greater for the larger sphere, which allows it to reach equilibrium of total pressure forces with less added submergence.

Because the hull of the sphere must be rotating with a small amount of slip as it propels through the water, the pressure forces of the flow are compicated. However, this simple relationship between pressure forces and diameter is supported quite clearly by the following observations:

- The 3' sphere experienced extreme negative lift.
- The 7' sphere experienced moderate negative lift.
- The original 10' sphere experienced "negative lift" only under conditions of high slip, i.e., when initial start up was not smooth. Dr. Dandini states that his 10' Hydrosphere actually experienced a positive lift once his craft obtained a low slip, high velocity mode.

It now appears that Hydrosphere models less than 10' in diameter cannot achieve a Froude hump, i.e., a low slip, high velocity mode of operation. An additional consideration is the fact that since flow pressure forces are sensitive to the radius of curvature of the surface, larger spheres may perform even better than diameter scaling implies.

IV. APPLICATION OF THE HYDROSPHERE CONCEPT TO ADVANCED MILITARY OPERATIONS

This section of the report provides some background on how the Hydrosphere concept could be effectively applied to military operations.

Over a period of years, the U.S. military has progressively acquired various tactical equipment and systems which have increasingly required the operation and/or storage of such equipment within portable shelters, Figure (9). There are many types of shelters in the military inventory, ranging from field tents to large portable buildings. The current trend is for development of a standard family of shelters.

An important consideration in establishing this concept is the shelter's mobility. Development of portable shelters for military application must consider the anticipated means for mobilizing or otherwise moving such facilities in the theatre of operations, to the beachhead and on to their ultimate destination in the field. There is a concentrated effort to insure that global mobility can be attained by a system which can readily be transported by any mode of commercial or military shipment, i.e., air, rail, truck, or sea transportation. The International Organization for Standardization (ISO) has established standards for containerized cargo boxes in sizes which are ideally suited to shelter applications to ensure the highest degree of multi-model transportability. The Merchant Marine, for example, has developed an extensive complement of container ships. Port facilities for handling ISO containers are also expanding. A typical standard family of shelters is shown in Figure (10). Given the advantages inherent with the ISO standardization for multi-mode shipment, the total mobility concept must also include means for transporting shelters from a central location across oceans to a port or beachhead, to an airstrip,

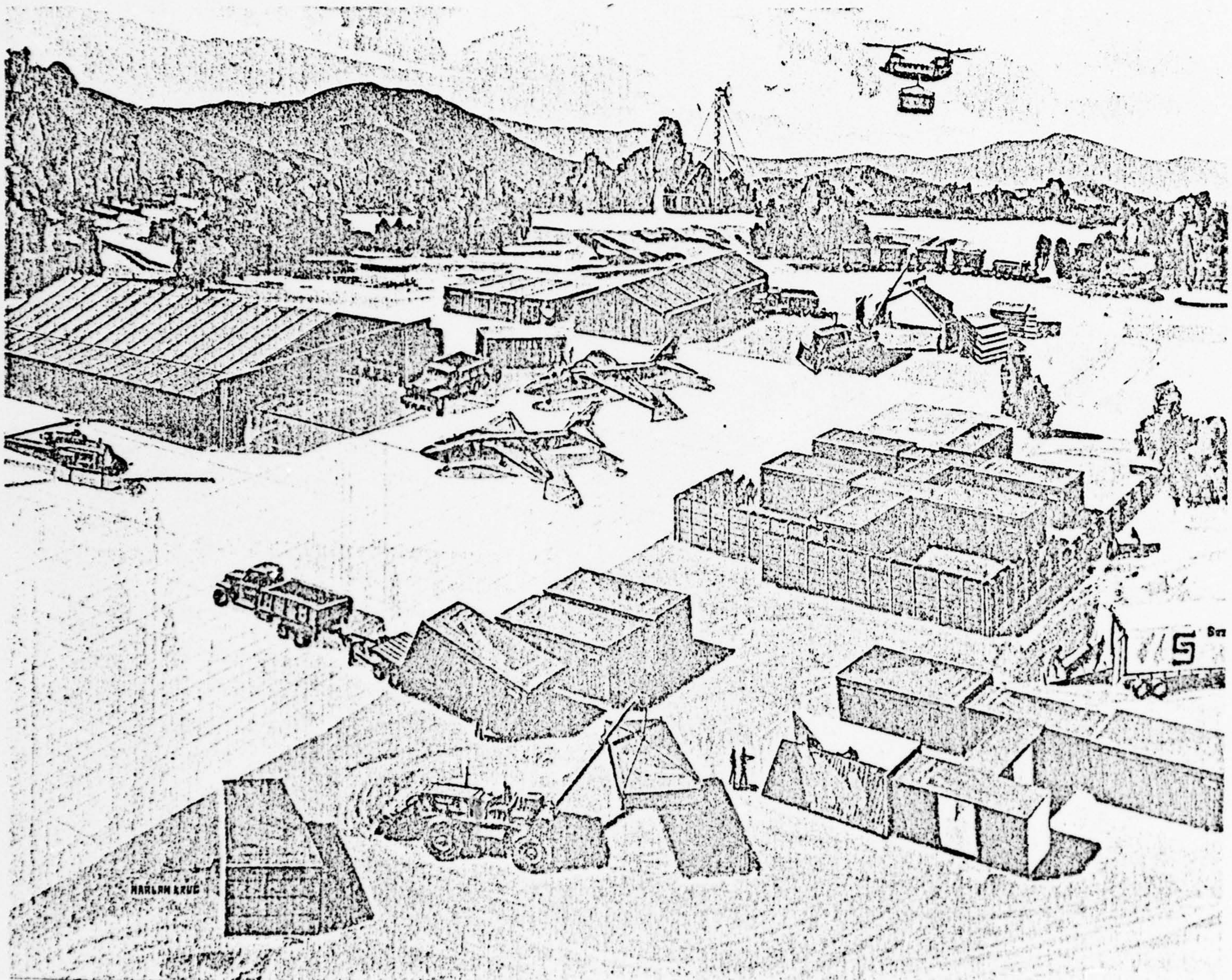


Figure (9). Example of military use of portable shelters.

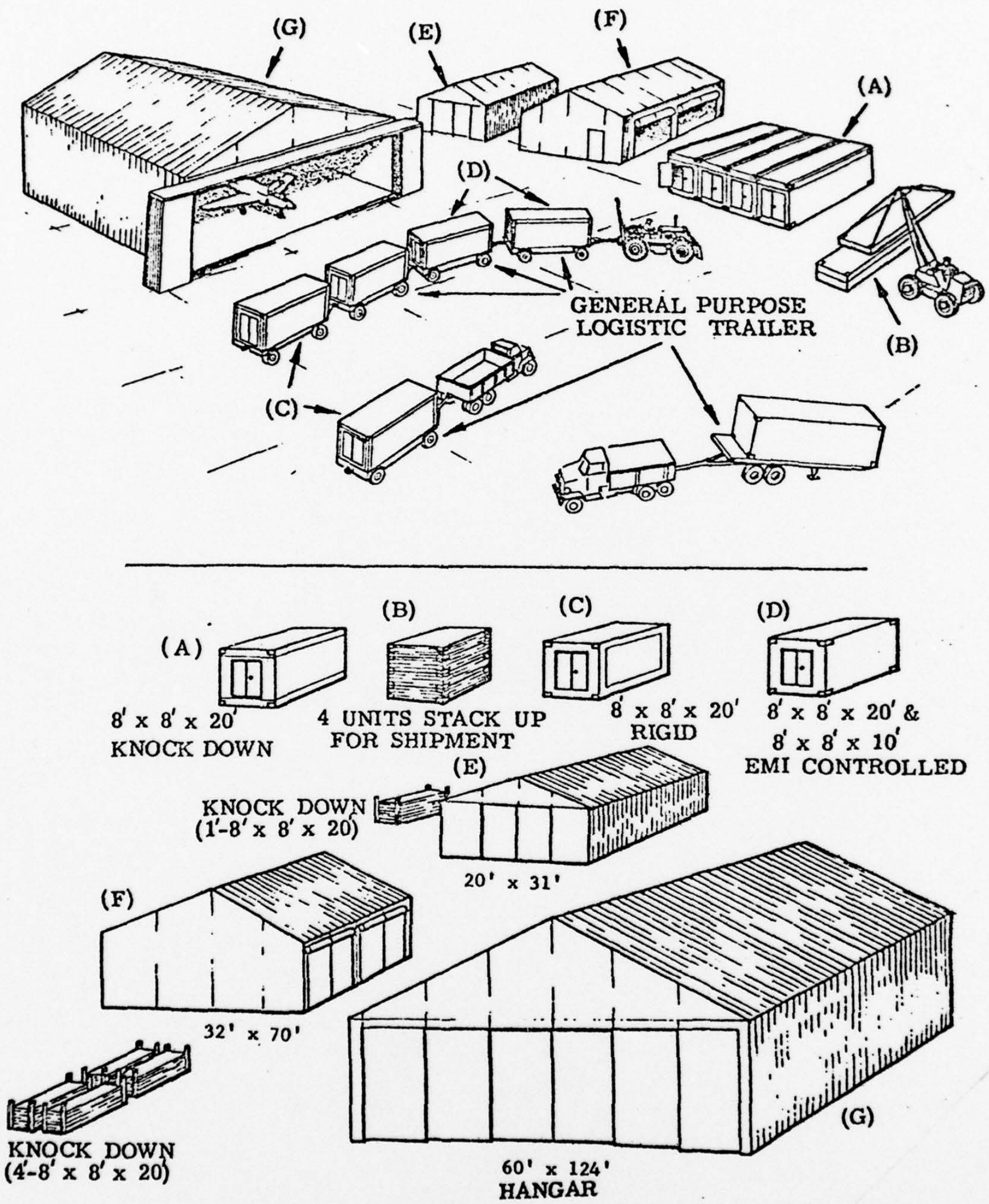


Figure (10). Example of a standard family of shelters.

etc. on to their ultimate point of usage. Such modes of transportation include special truck trailers, helicopters, railroad cars, and more recently a "cargo lander." A cargo lander, for example, is shown in Figure (11) where an 8 x 8 x 20 ft container from a landing craft is towed ashore by a newly developed Lightweight Amphibious Container Handler (LACH).

It is to this aspect of shelter transport that the Hydrosphere concept could be very effectively applied. The Hydrosphere concept could be directly applied to such amphibious operations. The Hydrosphere is an amphibious multi-terrain craft capable of providing efficient cargo carrying operations. An artist's concept of a Hydrosphere Cargo Lander (HCL) is shown in Figure (12). The HCL could be used, for example, to transport containers from a mother ship to shore, continue over the beach area and on directly to the desired point of usage. In doing this the HCL could replace the current use of helicopters and/or the use of a cargo lander with its associated landing craft. The HCL would be, therefore, an extremely efficient system for use in amphibious operations.

It is instructive to consider as an a example of this a 20 foot diameter Hydrosphere with a 20% submergence. Such a craft would have a total displacement capacity of approximately 27,184 lbs or 13.6 tons. The HCL itself would consume less than 20% of this displacement or some 5,437 lbs. The remaining displacement capacity would thus easily handle two 8 x 8 x 20 ft containers each weighing up to 10,000 lbs.

The data obtained so far on Hydrosphere performance definitely supports this concept.

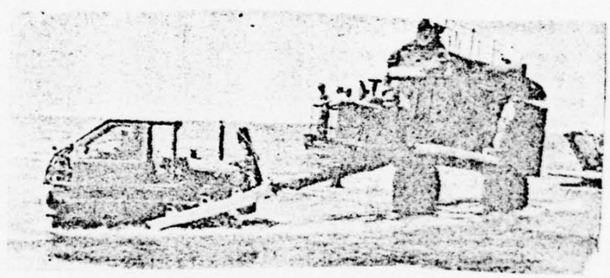
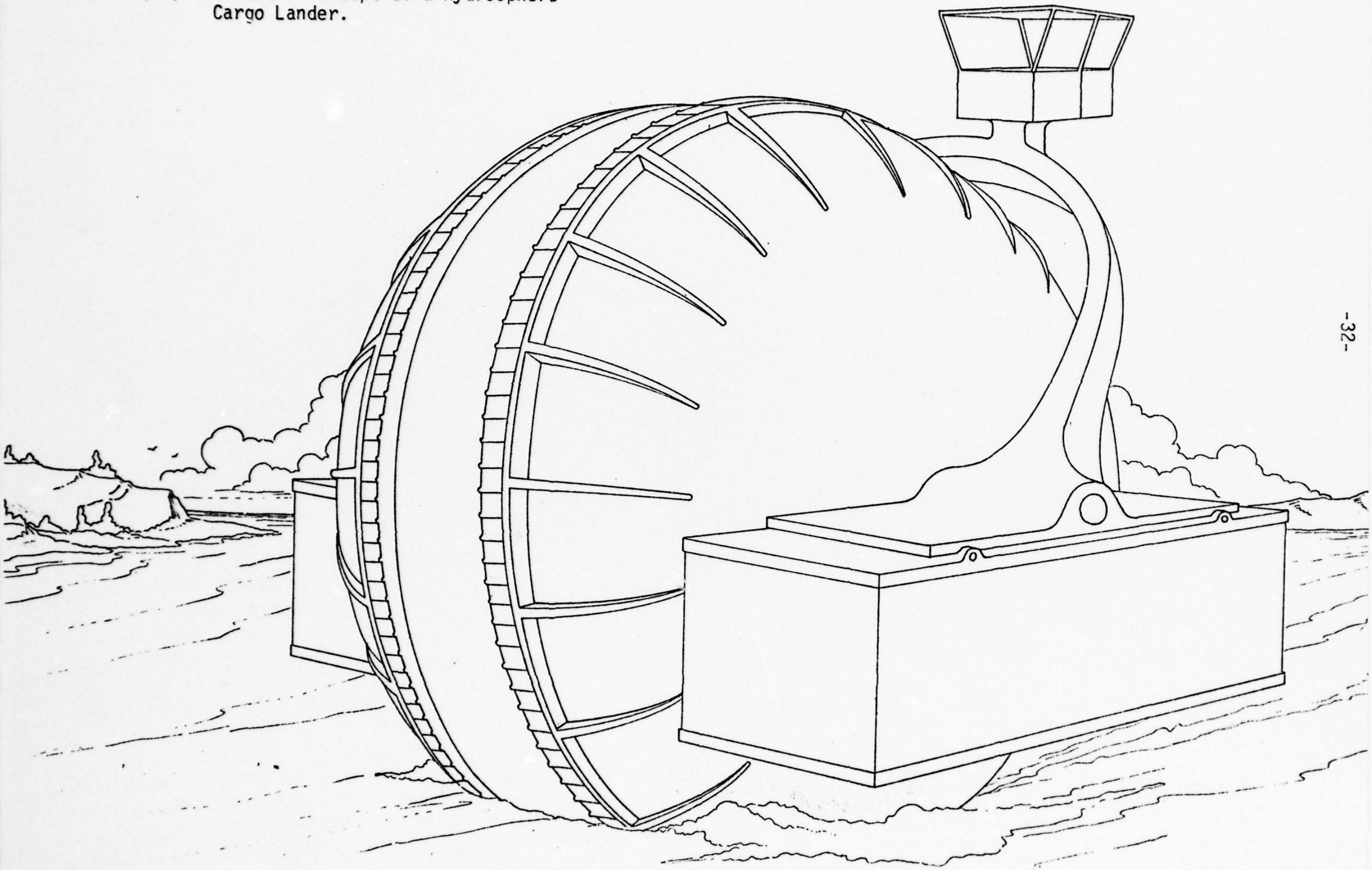


Figure (11). Photograph of the Navy Lightweight Amphibious Container Holder (LACH).

Figure (12) - Artist's concept of a Hydrosphere Cargo Lander.



V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Conclusions

Some very important conclusions can now be reached relating to the Hydrosphere concept.

(a) The Hydrosphere concept produces a stable operating system.

(b) Excellent lift drag ratios can be achieved even for Hydrospheres below 10' diameter (provided the slip is low).

(c) The Hydrosphere is an amphibious concept, thus providing the basis for an excellent multiterrain craft.

(d) It is now understood why the 7' Hydrosphere model could not achieve a higher forward velocity. The sensitivity of "negative lift" to diameter supports the fact that the Dandini 10' model did most probably achieve the performance claimed.

(e) The performance parameters V_{CL}/ω and A_W/V_S are quite useful in describing Hydrosphere performance.

(f) Froude scaling does not apply unless one considers the effect of the "negative lift," (or positive lift as the case may be).

(g) Vanes on the exterior of the Hydrosphere can affect craft performance. They must be carefully chosen to assist in the control of the boundary layer at the sphere-water interface.

(h) The Hydrosphere concept must definitely be directed to craft diameters greater than 10 feet.

(i) Provided that the negative lift concept is correct it is reasonable to expect that a 20 ft diameter Hydrosphere (at 15% slip) will achieve velocities in excess of 20 knots.

Recommendations for Future Work

(a) A larger model Hydrosphere should be constructed. This craft should be designed as an operational, mission directed system. The design should be accomplished within the already known parameters obtained by experimental procedures, i.e., the Hydrosphere is an efficient, stable, amphibious craft capable of handling large payloads. High speed testing of the larger Hydrosphere could also be accomplished in order to confirm the scaling parameters.

(b) The Hydrosphere concept could be immediately applied to the military shelter program. This concept was discussed in some detail in Section IV of this report.

(c) Computer "modeling" should be attempted during the design phases of a larger sphere. Some continued testing of the 7' sphere should be conducted especially for gathering data on the various possible vane configurations.

(d) The University of Nevada, Engineering Research and Development Center (ERDC), in cooperation with Scientific Engineering Systems, should prepare an immediate proposal outlining the design, fabrication, and testing of an operational, mission oriented craft. A twenty foot diameter system was discussed in Section IV of this report.

APPENDIX A

Summary of Data for Hydrosphere

Run Numbers (inclusive)	Date	Location	Notes
11-16, 27	9/23/75	Boca	Self propelled, free running
17-22, 26	9/23/75	Boca	Self propelled and towed
23-25	9/23/75	Boca	Tow locked sphere
28-30	9/23/75	Boca	Tow free rolling
31-38	9/7/76	Boca	Self propelled, free running
39-71	9/21/76	Boca	Self propelled, free running
72-91	9/28/76	Boca	Self propelled, free running
92-119	10/19/76	Lake Tahoe	Self propelled and towed
120-162	10/29/76	Lake Tahoe	Self propelled, free running
163-174	10/29/76	Lake Tahoe	Tow locked sphere
175-181	10/29/76	Lake Tahoe	Tow free rolling
182-186	10/29/76	Lake Tahoe	Tow reverse free rolling
187-205	10/30/76	Lake Tahoe	Underwater film, runs 202-205 were self propelled, towing
206-215	1/5/78	Salt Lake	Self propelled
216-229	1/7/78	Salt Lake	Self propelled
230-235	1/7/78	Salt Lake	Self propelled (vanes added)
236-241	1/7/78	Salt Lake	Tow locked sphere

Data taken Sept. 23, 1975

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
11	6.2	17.0	.36	27.4	5.88	4.0	8.0	—	0	0	.37	.37	.39	.22	.04
12	9.0	12.4	.73	50.0	8.06	5.5	36.4	—	0	0	3.2	3.2	.54	.73	.23
13	7.0	10.3	.68	35.7	9.71	6.6	38.0	—	0	0	3.1	3.1	.65	.41	.19
14	10.5	12.5	.84	57.1	8.00	5.5	45.6	—	0	0	4.5	4.5	.53	1.1	.33
15	8.0	9.0	.89	43.8	11.11	7.6	63.0	—	0	0	5.9	5.9	.74	.53	.31
16	5.7	16.6	.34	21.1	6.02	4.1	8.9	—	0	0	.39	.39	.40	.22	.04
17	7.0	13.0	.54	35.7	7.69	5.2	17.3	0	63	.88	1.2	2.1	.51	.55	.16
18	8.4	11.0	.76	46.4	9.09	6.2	37.0	0	106	1.75	3.4	5.2	.61	.83	.33
19	3.8	11.1	.34	-15.6	9.00	6.1	3.9	0	174	2.85	.17	3.0	.60	.49	.20
20	6.3	10.8	.58	28.6	9.26	6.3	30.5	0	138	2.32	2.2	4.5	.62	.67	.28
21	8.7	11.5	.76	48.3	8.70	5.9	33.1	0	91	1.44	3.1	4.5	.58	.82	.30
22	5.0	12.4	.40	10.0	8.06	5.5	small	0	129	1.89	small	1.89	.54	.43	.14
23	0.0	22.5	0	—	4.44	3.0	—	0	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]	[illegible]

Data taken Sept. 23, 1975

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	γ
24	0.0	16.0	0	–	6.25	4.3	–	0	100	1.14	–	1.14	.42	.56	.11
25	0.0	13.1	0	–	7.63	5.2	–	0	168	2.33	–	2.33	.51	.63	.18
26	9.2	10.6	.87	51.1	9.43	6.4	37.9	0	200	3.43	4.0	7.43	.63	1.1	.46
27	5.0	15.5	.32	10.0	6.45	4.4	8.0	–	0	0	.33	.33	.43	.15	.03
28	3.1	14.0	.22	-31.1	7.14	4.9	–	0	54	.70	–	.70	.48	.23	.06
29	3.2	12.5	.26	-28.9	8.00	5.5	–	0	96	1.40	–	1.40	.53	.33	.10
30	3.2	11.4	.28	-28.9	8.77	6.0	–	0	173	2.76	–	2.76	.58	.49	.18

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
31	9.4	25.0	.38	27.43	6.0	4.09	4.0	—	—	0	.20	.20	.40	0.11	.020
32	17.0	22.0	.77	59.87	6.82	4.65	38.9	—	—	0	3.63	3.63	.45	1.37	.311
33	10.8	22.0	.49	36.84	6.82	4.65	16.9	—	—	0	1.07	1.07	.45	.40	.092
34	10.3	20.0	.52	33.77	7.50	5.11	15.0	—	—	0	1.00	1.00	.50	.28	.078
35	12.0	21.0	.57	43.16	7.14	4.87	17.9	—	—	0	1.31	1.31	.48	.43	.107
36	11.8	16.0	.74	42.19	9.38	6.39	34.0	—	—	0	3.08	3.08	.62	.45	.192
37	14.0	21.0	.67	51.28	7.14	4.87	—	—	—	0	—	—	.48	—	—
38	8.0	28.5	.28	14.73	5.26	3.59	—	—	—	0	—	—	.35	—	—
39	6.5	19.0	.34	-4.94	7.89	5.38	—	—	—	0	—	—	.53	—	—
40	12.0	23.0	.52	43.16	6.52	4.45	—	—	—	0	—	—	.43	—	—
41	9.5	22.0	.43	28.20	6.82	4.65	—	—	—	0	—	—	.45	—	—
42	11.0	26.0	.42	37.99	5.77	3.93	—	—	—	0	—	—	.38	—	—
43	9.0	21.0	.43	24.21	7.14	4.87	—	—	—	0	—	—	.48	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
44	10.5	23.5	.45	35.04	6.38	4.35	—	—	—	0	—	—	.43	—	—
45	9.5	16.0	.59	28.20	9.38	6.39	—	—	—	0	—	—	.62	—	—
46	12.5	23.0	.54	45.43	6.52	4.45	—	—	—	0	—	—	.43	—	—
47	12.0	22.0	.55	43.16	6.82	4.65	—	—	—	0	—	—	.45	—	—
48	10.5	19.0	.55	35.04	7.89	5.38	—	—	—	0	—	—	.53	—	—
49	13.5	21.5	.63	49.47	6.98	4.76	—	—	—	0	—	—	.46	—	—
50	11.5	19.0	.61	40.68	7.89	5.38	—	—	—	0	—	—	.53	—	—
51	13.5	21.5	.63	49.47	6.98	4.76	—	—	—	0	—	—	.46	—	—
52	11.5	18.5	.62	40.68	8.11	5.53	—	—	—	0	—	—	.54	—	—
53	12.0	18.5	.65	43.16	8.11	5.53	—	—	—	0	—	—	.54	—	—
54	10.5	15.0	.70	35.04	10.00	6.82	—	—	—	0	—	—	.67	—	—
55	14.0	21.0	.67	51.28	7.14	4.87	—	—	—	0	—	—	.48	—	—
56	12.5	18.0	.69	45.43	8.33	5.68	—	—	—	0	—	—	.56	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
57	15.5	20.5	.76	55.99	7.32	4.99	—	—	—	0	—	—	.49	—	—
58	14.0	18.0	.78	51.28	8.33	5.68	—	—	—	0	—	—	.56	—	—
59	14.5	19.5	.74	52.96	7.69	5.24	—	—	—	0	—	—	.51	—	—
60	12.0	18.5	.65	43.16	8.11	5.53	—	—	—	0	—	—	.54	—	—
61	13.0	18.5	.70	47.53	8.11	5.53	—	—	—	0	—	—	.54	—	—
62	10.0	17.0	.59	31.79	8.82	6.62	23.5	—	—	0	1.76	1.76	.59	0.31	0.12
63	8.5	22.0	.39	19.75	6.82	4.65	8.9	—	—	0	.45	.45	.45	.17	.039
64	8.2	23.0	.36	16.81	6.52	4.45	6.0	—	—	0	.28	.28	.43	.12	.025
65	12.0	22.5	.53	43.16	6.67	4.55	27.9	—	—	0	1.87	1.87	.44	.76	.164
66	12.5	23.0	.54	45.43	6.52	4.45	18.0	—	—	0	1.26	1.26	.43	.54	.113
67	11.1	19.0	.58	38.55	7.89	5.38	30.9	—	—	0	2.24	2.24	.53	.55	.166
68	15.6	22.0	.71	56.27	6.82	4.65	34.0	—	—	0	2.97	2.97	.45	1.12	.255
69	13.3	19.5	.68	48.71	7.69	5.24	33.9	—	—	0	2.85	2.85	.51	.75	[illegible]

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
70	15.6	21.0	.74	56.27	7.14	4.87	37.0	—	—	0	3.34	3.34	.48	1.10	.274
71	10.0	14.0	.71	31.79	10.71	7.31	32.4	—	—	0	2.85	2.85	.71	.28	.160
72	14.0	26.0	.54	51.28	5.77	3.93	10.0	—	—	0	.70	.70	.38	.44	.071
73	12.2	29.0	.42	44.09	5.17	3.53	8.9	—	—	0	.49	.49	.34	.42	.055
74	16.6	22.5	.74	58.91	6.67	4.55	19.0	—	—	0	1.80	1.80	.44	.73	.158
75	15.4	25.0	.62	55.71	6.00	4.09	15.9	—	—	0	1.26	1.26	.40	.70	.123
76	18.0	20.0	.90	62.10	7.50	5.11	36.0	—	—	0	3.96	3.96	.50	1.13	.309
77	17.7	23.0	.77	61.46	6.52	4.45	33.9	—	—	0	3.21	3.21	.43	1.39	.288
78	18.2	24.5	.74	62.52	6.12	4.17	33.0	—	—	0	3.03	3.03	.41	1.58	.290
79	17.5	23.5	.74	61.02	6.38	4.35	32.7	—	—	0	2.99	2.99	.43	1.38	.270
80	12.5	29.0	.43	45.43	5.17	3.53	14.0	—	—	0	.78	.78	.34	.68	.088
81	12.0	27.0	.44	43.16	5.56	3.79	12.9	—	—	0	.73	.73	.37	.51	.077
82	13.3	27.0	.49	44.71	5.56	3.79	10.0	—	—	0	1.4	1.4	[illegible]	[illegible]	[illegible]

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
83	13.8	27.5	.50	50.57	5.45	3.72	12.9	—	—	0	.84	.84	.36	.62	.090
84	12.8	27.5	.47	46.71	5.45	3.72	11.0	—	—	0	.66	.66	.36	.49	.071
85	15.0	24.0	.63	54.52	6.25	4.26	25.9	—	—	0	2.06	2.06	.42	1.01	.193
86	16.2	25.0	.65	57.89	6.00	4.09	16.0	—	—	0	1.34	1.34	.40	.74	.131
87	16.0	25.0	.64	57.37	6.00	4.09	21.9	—	—	0	1.79	1.79	.40	.99	.175
88	15.6	25.0	.62	56.27	6.00	4.09	18.0	—	—	0	1.44	1.44	.40	.80	.140
89	15.2	24.0	.63	55.12	6.25	4.26	24.9	—	—	0	1.99	1.99	.42	.98	.186
90	17.0	26.0	.65	59.87	5.77	3.93	25.6	—	—	0	2.10	2.10	.38	1.31	.213
91	16.0	24.5	.65	57.37	6.12	4.17	—	—	—	0	—	—	.41	—	—
92	4.6	29.0	.16	-48.29	5.17	3.53	2.1	27.5	25	.21	.04	.25	.34	.22	.029
93	4.5	25.0	.18	-51.58	6.00	4.09	small	27.0	50	.49	0	.49	.40	.27	.048
94	8.6	21.5	.40	20.68	6.98	4.76	4.9	27.5	72	.81	.26	1.07	.46	.38	.090
95	4.5	31.0	.15	-51.58	4.84	3.30	2.0	27.3	90	.70	.04	.74	.32	.79	.089

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
96	10.4	21.0	.50	34.41	7.14	4.87	17.9	26.3	26	.30	1.14	1.44	.48	.47	.118
97	12.9	24.0	.54	47.12	6.25	4.26	3.9	29.0	125	1.24	.27	1.52	.42	.75	.142
98	11.7	19.5	.60	41.70	7.69	5.24	22.9	29.5	190	2.31	1.75	4.06	.51	1.07	.309
99	9.6	18.0	.53	28.94	8.33	5.68	15.9	22.5	208	2.91	1.09	4.00	.56	.83	.281
100	7.7	18.0	.43	11.41	8.33	5.68	8.9	22.0	198	2.78	.50	3.28	.56	.68	.231
101	9.0	18.5	.49	24.21	8.11	5.53	—	—	210	0	—	—	.54	—	—
102	11.4	18.0	.63	40.16	8.33	5.68	27.9	21.5	110	1.55	2.22	3.77	.56	.78	.265
103	8.6	20.5	.42	20.68	7.32	4.19	9.9	24.4	115	1.39	.54	1.93	.49	.59	.154
104	9.4	20.0	.47	27.43	7.50	5.11	12.9	26.0	115	1.41	.78	2.19	.50	.62	.171
105	8.6	21.0	.41	20.68	7.14	4.87	11.9	25.0	120	1.41	.63	2.04	.48	.67	.167
106	8.8	20.0	.44	22.49	7.50	5.11	13.9	24.0	126	1.57	.79	2.36	.50	.67	.184
107	12.8	20.0	.64	46.71	7.50	5.11	23.9	25.5	90	1.11	1.94	3.05	.50	.87	.238
108	13.9	20.5	.68	50.93	7.32	4.99	23.9	[illegible]	93	1.12	2.05	3.19	.49	.97	[illegible]

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RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
109	12.5	20.5	.61	45.43	7.32	4.99	20.9	22.3	67	.82	1.63	2.45	.49	.75	.196
110	12.5	22.0	.57	45.43	6.82	4.65	15.9	26.0	40	.45	1.16	1.61	.45	.61	.138
111	12.5	22.5	.56	45.43	6.67	4.55	18.9	25.8	45	.49	1.35	1.84	.44	.74	.161
112	12.2	22.5	.54	44.09	6.67	4.55	17.9	28.0	26	.28	1.25	1.52	.44	.62	.133
113	13.5	23.5	.57	49.47	6.38	4.35	16.9	27.5	28	.29	1.25	1.54	.43	.71	.141
114	13.1	23.5	.56	47.93	6.38	4.35	18.9	27.0	20	.21	1.35	1.56	.43	.72	.143
115	14.5	24.5	.59	52.96	6.12	4.17	20.9	28.0	20	.20	1.58	1.78	.41	.93	.170
116	12.7	24.5	.52	46.29	6.12	4.17	12.9	28.5	25	.24	.87	1.11	.41	.58	.106
117	11.8	24.5	.48	42.19	6.12	4.17	11.9	28.0	4	.04	.74	.78	.41	.41	.075
118	12.0	27.0	.44	43.16	5.56	3.79	9.9	29.0	8	.07	.57	.64	.37	.45	.067
119	11.0	25.0	.44	37.99	6.00	4.09	8.9	23.0	55	.55	.51	1.06	.40	.59	.103
120	12.2	34.0	.36	44.09	4.41	3.01	6.0	—	—	0	.28	.28	.29	.39	.037
121	11.3	34.0	.33	[illegible]	[illegible]	3.01	4.9	—	—	0	.21	.21	.29	.30	[illegible]

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UN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
122	11.9	35.0	.34	42.68	4.29	2.92	1.0	—	—	0	.04	.04	.29	.07	.005
123	11.5	35.5	.32	40.68	4.23	2.88	1.9	—	—	0	.08	.08	.28	.13	.011
124	11.0	32.5	.34	37.99	4.62	3.15	6.0	—	—	0	.26	.26	.31	.32	.033
125	11.1	36.0	.31	38.55	4.17	2.84	0.1	—	—	0	.004	.004	.28	.01	.0006
126	11.3	33.5	.34	39.63	4.48	3.05	2.5	—	—	0	.11	.11	.30	.15	.021
127	11.5	35.5	.32	40.68	4.23	2.88	0.4	—	—	0	.017	.017	.28	.03	.002
128	13.3	29.0	.46	48.71	5.17	3.53	16.0	—	—	0	.95	.95	.34	.82	.108
129	13.8	29.0	.48	50.57	5.17	3.53	6.9	—	—	0	.43	.43	.34	.37	.049
130	17.2	27.0	.64	60.34	5.56	3.79	23.0	—	—	0	1.86	1.86	.37	1.30	.196
131.	15.0	28.0	.54	54.52	5.36	3.65	13.9	—	—	0	.97	.97	.36	.76	.106
32	14.0	27.0	.52	51.28	5.56	3.79	12.0	—	—	0	.81	.81	.37	.56	.085
33	16.7	27.5	.61	59.15	5.45	3.72	20.9	—	—	0	1.62	1.62	.36	1.20	.174
134	16.1	27.0	.60	57.63	5.56	3.79	20.0	—	—	0	1.53	1.53	.37	1.07	.161

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UN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
135	15.5	29.0	.53	55.99	5.17	3.53	12.9	—	—	0	.89	.89	.34	.77	.101
136	15.1	26.5	.57	54.83	5.66	3.86	18.0	—	—	0	1.32	1.32	.38	.87	.136
137	15.3	29.0	.53	55.42	5.17	3.53	19.9	—	—	0	1.34	1.34	.34	1.16	.152
138	11.5	32.5	.35	40.68	4.62	3.15	4.0	—	—	0	.83	.83	.31	.22	.023
139	17.0	37.5	.45	59.87	4.00	2.73	14.9	—	—	0	.87	.87	.27	1.63	.127
140	13.0	27.5	.47	47.53	5.45	3.72	18.5	—	—	0	1.12	1.12	.36	.83	.120
141	15.2	28.0	.54	55.12	5.36	3.65	22.9	—	—	0	1.58	1.58	.36	1.23	.172
142	15.8	27.0	.59	56.83	5.56	3.79	17.0	—	—	0	1.28	1.28	.37	.90	.135
143	16.6	27.0	.61	58.91	5.56	3.79	20.9	—	—	0	1.64	1.64	.37	1.15	.173
144	16.9	25.5	.66	59.64	5.88	4.01	25.0	—	—	0	2.10	2.10	.39	1.24	.209
145	14.1	31.0	.45	51.62	4.84	3.30	15.9	—	—	0	.93	.93	.32	.99	.112
146	12.4	30.0	.41	44.99	5.00	3.41	9.0	—	—	0	.48	.48	.33	.46	.056
147	13.0	33.5	.39	47.5[illegible]	4.48	3.05	4.9	—	—	0	.25	.25	.30	.33	.033

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE $\measuredangle$	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	F_r	C_D	η_t
148	10.5	32.0	.33	35.04	4.69	3.20	10.0	—	—	0	.43	.43	.31	.50	.054
149	13.1	31.5	.42	47.93	4.76	3.25	7.9	—	—	0	.43	.43	.32	.48	.053
150	16.8	26.5	.63	59.40	5.66	3.86	20.0	—	—	0	1.62	1.62	.38	1.07	.167
151	17.0	46.5	.37	59.87	3.30	2.25	6.9	—	—	0	.29	.29	.22	.96	.051
152	18.7	31.5	.59	63.52	4.76	3.25	23.0	—	—	0	1.74	1.74	.32	1.93	.214
153	14.9	30.5	.49	54.22	4.92	3.35	9.9	—	—	0	.63	.63	.33	.63	.075
154	17.8	25.5	.70	61.68	5.88	4.01	24.0	—	—	0	2.12	2.12	.39	1.25	.211
155	16.8	26.5	.63	59.40	5.66	3.86	15.9	—	—	0	1.30	1.30	.38	.86	.134
156	16.8	25.5	.66	59.40	5.88	4.01	22.0	—	—	0	1.85	1.85	.39	1.09	.184
157	16.4	26.0	.63	58.41	5.77	3.93	22.9	—	—	0	1.84	1.84	.38	1.15	.187
158	16.3	25.5	.64	58.15	5.88	4.01	25.0	—	—	0	2.02	2.02	.39	1.19	.201
159	16.0	27.0	.59	57.37	5.56	3.79	25.9	—	—	0	1.94	1.94	.37	1.36	.204
160	16.0	25.5	.63	57.37	5.88	4.01	20.0	—	—	0	1.11	1.11	.39	.95	[illegible]

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
161	14.0	29.5	.47	51.28	5.08	3.47	19.9	—	—	0	1.21	1.21	.34	1.10	.139
162	13.0	24.5	.53	47.53	6.12	4.17	15.0	—	—	0	1.03	1.03	.41	.54	.098
163×	0	29.5	0	—	5.08	3.47	—	26	60	.50	0	.50	.34	.46	.058
164	0	29.5	0	—	5.08	3.47	—	26	70	.58	0	.58	.34	.53	.067
165×	0	39.5	0	—	3.80	2.59	—	26	25	.16	0	.16	.25	.34	.025
166	0	27.0	0	—	5.56	3.79	—	26	99	.90	0	.90	.37	.63	.095
167×	0	24.0	0	—	6.25	4.26	—	26	133	1.36	0	1.36	.42	.67	.127
168	0	28.0	0	—	5.36	3.65	—	26	104	.91	0	.91	.36	.71	.099
169	0	20.5	0	—	7.32	4.99	—	26	203	2.43	0	2.43	.49	.74	.194
170	0	29.0	0	—	5.17	3.53	—	26	72	.61	0	.61	.34	.53	.069
171	0	20.0	0	—	7.50	5.11	—	26	225	2.76	0	2.76	.50	.78	.215
172	0	32.0	0	—	4.69	3.20	—	26	52	.40	0	.40	.31	.46	.050
173×	0	22.5	0	—	6.67	4.55	—	26	153	1.67	0	1.67	.44	.68	.146

* NOT RECORDED

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
174	0	46.0	0	—	3.26	2.22	—	26	26	.14	0	.14	.22	.48	.025
175	*	21.5	—	—	6.98	4.76	—	26	152	1.73	0	1.73	.46	.61	.145
176	*	27.5	—	—	5.45	3.72	—	26	50	.45	0	.45	.36	.33	.048
177	10	20.5	.49	31.78	7.32	4.99	—	26	242	2.89	0	2.89	.49	.89	.231
178	*	24.0	—	—	6.25	4.26	—	26	150	1.53	0	1.53	.42	.75	.143
179	8	23.0	.35	14.75	6.52	4.45	—	26	118	1.26	0	1.26	.43	.54	.113
180	*	32.5	—	—	4.62	3.15	—	26	28	.21	0	.21	.31	.26	.027
181	*	24.5	—	—	6.12	4.17	—	26	85	.85	0	.85	.41	.44	.081
182	*	30.0	—	—	5.00	3.41	—	26	42	.34	0	.34	.33	.33	.040
183	8	21.0	.38	14.75	7.14	4.87	—	26	208	2.43	0	2.43	.48	.80	.199
184	8	25.0	.32	14.75	6.00	4.09	—	26	108	1.06	0	1.06	.40	.59	.103
185	7	22.5	.31	2.57	6.67	4.55	—	26	160	1.74	0	1.74	.44	.71	.153
186	7	31.0	.23	2.57	4.84	3.30	—	[illegible]	[illegible]	.74	0	.74	[illegible]	[illegible]	[illegible]

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UN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
187	10.0	42.0	.24	31.79	3.57	2.44	—	—	—	0	—	—	.24	—	—
188		RUN ABORTED DUE TO ENGINE SHUT DOWN													
189	10.5	42.0	.25	35.04	3.57	2.44	—	—	—	0	—	—	.24	—	—
90	12.0	31.5	.38	43.16	4.76	3.25	—	—	—	0	—	—	.32	—	—
91	12.0	31.0	.39	43.16	4.84	3.30	—	—	—	0	—	—	.32	—	—
92	12.0	29.5	.41	43.16	5.08	3.47	—	—	—	0	—	—	.34	—	—
93	12.5	29.5	.42	45.43	5.08	3.47	—	—	—	0	—	—	.34	—	—
94	12.5	28.0	.45	45.43	5.36	3.65	—	—	—	0	—	—	.36	—	—
95	12.5	29.5	.42	45.43	5.08	3.47	—	—	—	0	—	—	.34	—	—
96	12.0	27.5	.44	43.16	5.45	3.72	—	—	—	0	—	—	.36	—	—
97	13.0	30.0	.43	47.53	5.00	3.41	—	—	—	0	—	—	.33	—	—
98	11.0	31.0	.35	37.99	4.84	3.30	—	—	—	0	—	—	.32	—	—
99	11.0	29.5	.37	37.99	5.08	3.47	—	—	—	0	—	—	.34	—	—

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	$\theta°$	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
200	10.5	45.0	.23	35.04	3.33	2.27	*	—	—	0	—	—	.22	—	—
201	10.5	32.5	.32	35.04	4.62	3.15	*	—	—	0	—	—	.31	—	—
202	8.5	25.0	.34	19.75	6.00	4.09	*	26	38	.37	—	—	.40	.21	—
203	6.5	24.5	.27	-4.94	6.12	4.17	*	26	35	.35	—	—	.41	.18	—
204	7.5	27.0	.28	9.05	5.56	3.79	*	26	30	.27	—	—	.37	.19	—
205	8.5	21.0	.40	19.75	7.14	4.87	*	26	85	.99	—	—	.48	.33	—

* NOT MEASURED BECAUSE CAMERA WAS USED UNDERWATER, IN EACH CASE SPHERE POWER WAS VERY LOW.

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$(7.48)(\omega)(\sin\theta)$

data calculated [illegible] 13 JAN 78

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LTR +8.9
RTL +8.0

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η_t
206	14	26.83	0.52	51.28	5.59	3.81	14.08	—	—	—		0.95	0.37	0.63	0.099
207	14	28.15	0.5	51.28	5.33	3.63	10	—	—	—		0.65	0.36	0.5	0.071
208	19	25.4	0.75	64.1	5.91	4.03	44.23					3.91	0.39	2.21	0.387
209	14	27.85	0.5	51.28	5.39	3.68	19.13					1.23	0.36	0.92	0.134
210	15	27.15	0.55	54.53	5.52	3.76	19.78					1.39	0.37	0.96	0.147
211	11	35.31	0.31	37.99	4.25	2.9	16.56					0.66	0.28	1.0	0.091
212	16	27.3	0.59	57.37	5.49	3.74	21.59					1.62	0.37	1.14	0.173
213	19	24.95	0.76	64.1	6.01	4.1	50.53					4.39	0.4	2.36	0.427
214	14.5	28.3	0.51	52.96	5.3	3.61	17.17					1.13	0.35	0.89	0.125
215	17.25	24.4	0.71	60.46	6.15	4.19	42.46					3.59	0.41	1.8	0.342
216	14.5	32.1	0.45	52.96	4.67	3.18	14.06					0.82	0.31	0.94	0.103
217	10.75	27.15	0.4	36.55	5.52	3.76	11.4					0.59	0.37	0.41	0.063
218	13.5	28.7	0.47	49.47	5.23	3.57	9.83					0.6	0.35	0.49	0.067

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE ~~HP~~	TOTAL HP	Fr	C_D	η
219	13.25	24.53	0.54	48.52	6.11	4.17	16.65					1.16	0.41	0.59	0.111
220	15.5	28.3	0.55	55.99	5.3	3.61	18.81					1.33	0.35	1.04	0.147
221	13.75	25.1	0.55	56.69	5.98	4.08	18.21					1.29	0.4	0.7	0.126
222	13.5	29.3	0.46	49.47	5.12	3.49	14.75					0.88	0.34	0.77	0.101
223	15.5	25.55	0.61	55.99	5.87	4.0	18.81					1.47	0.39	0.85	0.147
224	13.75	24.8	0.55	56.69	6.05	4.13	21.9					1.53	0.4	0.81	0.148
225	15	25.53	0.59	54.53	5.88	4.01	22.69					1.7	0.39	0.98	0.169
226	14.5	23.9	0.61	5296	6.28	4.28	26.4					2.03	0.42	0.96	0.189
227	14	26.6	0.53	5128	5.64	3.85	19.5					1.32	0.38	0.86	0.137
228	15.25	24.15	0.63	55.27	6.21	4.23	29.96					2.35	0.41	1.14	0.221
229	16	25.3	0.63	57.37	5.93	4.04	22.56					1.81	0.39	1.01	0.179
230	13	21.9	0.59	4753	6.85	4.67	43.15					3.02	0.46	1.1	0.258
231	13.75	22.65	0.61	5669	6.62	4.51	29					2.21	0.44	0.89	0.195

RUN #	NO. REV	TIME (sec)	ω (rev/sec)	% SLIP	Vel. (ft/sec)	Vel. (mph)	θ°	ROPE ∡	ROPE FORCE (lbs.)	TOW HP	SPHERE HP	TOTAL HP	Fr	C_D	η
232	12.75	22.5	0.58	46.5	6.77	4.62	37.84					2.66	0.45	1.0	0.23
233	11.75	27.75	0.42	41.95	5.46	3.69	13.5					0.73	0.36	0.54	0.079
234	12.5	25.35	0.49	45.43	5.92	4.04	22.4					1.4	0.39	0.79	0.138
235	13	23.25	0.56	47.53	6.45	4.4	30.75					2.14	0.43	0.93	0.194
THE FOLLOWING RUNS ARE TOW RUNS 4 JAN 78															
236		25.2			5.95	4.06			127.14	1.38			0.4	0.76	0.14
237		24.5			6.12	4.17			114	1.27			0.41	0.65	0.12
238		20.25			7.41	5.05			285.45	3.85			0.49	1.1	0.3
239		25.2			5.95	4.06			120.23	1.3			0.4	0.72	0.13
240		31.7			4.73	3.23			47.4	0.41			0.32	0.45	0.05
241		22.15			6.77	4.62			196.88	2.42			0.45	0.91	0.21

APPENDIX B

Film Record

Film Record

Run #	Film Footage	Run #	Film Footage
31	0-17	74	27-40
32	17-36	75	40-53
33	36-53	76	53-64
34	53-72	77	64-75
35	72-86	78	75-87
36	86-105	79	87-96
37	none	80	none
38	none	81	5-8
39	on boat	82	8-19
40	on boat	83	19-30
.	.	84	30-41
61	on boat	85	41-49
62	5-7	86	49-59
63	7-12	87	59-73
64	12-23	88	73-82
65	23-33	89	82-91
66	33-43	90	92-104
67	43-52	91	none
68	52-63	92	4-15
69	63-73	93	15-23
70	73-83	94	23-34
71	83-90	95	34-48
72	5-12	96	48-58
73	12-27	97	58-70

Run #	Film Footage	Run #	Film Footage
98	70-81	124	154-168
99	81-90	125	0-20
100	90 -	126	20-38
101	none	127	38-55
102	0-13	128	55-69
103	13-24	129	69-84
104	24-36	130	84-100
105	36-49	131	103-120
106	52-63	132	0-15
107	63-73	133	15-29
108	73-84	134	29-43
109	84-95	135	43-57
110	95-107	136	57-71
111	0-8	137	71-85
112	8-20	138	85-101
113	20-32	139	101-120
114	32-43	140	0-14
115	43-55	141	14-27
116	55-66	142	27-40
117	69-79	143	40-53
118	79-88	144	53-66
119	0-13	145	66-81
120	83-101	146	81-95
121	101-118	147	95-110
122	118-136	148	0-16
123	136-154	149	16-31

Run #	Film Footage	Run #	Film Footage
150	31-44	213	95-109
151	44-63	214	19-33 (reelII)
152	63-78	215	33-45
153	78-92	216	10-27 (reel III)
154	92-105	217	27-39
155	0-14	218	39-53
156	14-28	219	53-64
157	28-41	220	64-78
158	41-54	221	79-90
159	54-67	222	90-105
160	67-80	223	0-12 (reel IV)
161	80-94	224	12-24
162	96-108	225	24-38
163	none	226	38-48
164	none	227	48-64
165	none	228	64-75
:	:	229	75-88
186	none	230	23-32 (reel V)
187	underwater	231	32-45
188	underwater	232	45-57
:	:	233	57-75
205	underwater	234	75-87
206	0-20 (reel I)	235	87-102
207	20-32	236	none
208	32-43	237	none
209	43-55	238	none
210	55-69	239	none
211	69-82	240	none
212	82-95	241	none